Liquid Metal Ultrasound Velocimetry in a High Current Environment

Marco Starace, Norbert Weber, Martin Seilmayer, Tom Weier, Frank Stefani and Sven Eckert
Helmholtz-Zentrum Dresden − Rossendorf, Bautzner Landstraße 400, 01328 Dresden, Germany

Ultrasound Doppler velocimetry is an important tool for the characterization of liquid metal flows, including those caused by magnetohydrodynamic instabilities. Here we consider the Tayler Instability (TI), which is driven by a high current flowing through the system. This can entail a great deal of electromagnetic noise, which must be decoupled from the signal produced by ultrasound scatterers within the liquid metal. In the experiment described herein, two ultrasound transducers encased within a copper electrode are in contact with a cylindrical liquid GaInSn column. Currents in the order of several kA produced by a switching-mode power supply flow through the electrode and the liquid GaInSn, resulting in the TI, which causes vortices with vertical velocity components in the range of several mm/s to appear. Noise produced by the power supply was significantly reduced by adding film capacitors and toroidal cores, including a common-mode choke to the circuit. Electromagnetic interference was further reduced by adding toroidal and split cores to the coaxial cables connecting the ultrasound transducers to the velocimeter, with the latter drawing power through an isolating transformer. These precautions permitted the retrieval of reliable velocity data, which generally agree with previously conducted B_z-measurements.

Keywords: Liquid metals, magnetohydrodynamics, Tayler Instability, noise suppression

1 INTRODUCTION

As societies increasingly rely on renewable sources, such as solar and wind energy for electricity generation, they must develop a concomitantly larger energy storage infrastructure, in order to buffer differences between production and demand. Liquid metal batteries have been proposed as a means of large scale and short-term storage. They contain three stacked liquid phases consisting of a cathode metal alloy and an anode metal, separated from one another by a layer of electrolyte, such as an ionic liquid. The advantage of such systems for energy storage are their scalability, simple and self-assembling construction, long charge cycle life, high current density and reasonable material costs. Their disadvantages are low voltages, high working temperatures, as well as hydromagnetic instabilities that could occur during the charging and discharging processes.

A possible problem caused by the flow resulting from such instabilities could be the local displacement of the electrolyte layer, which would bring the anode and cathode liquids into direct contact, thus shorting out the battery.

The Tayler Instability (TI) is the focus of the experiment discussed in this paper. An electric current axially flowing through a cylindrical column composed of a conducting fluid results in an azimuthal magnetic field, which yields an inward radial Lorentz force. A slight perturbation in the system will break the azimuthal symmetry of the magnetic field and radial symmetry of the force. Below a certain critical current the Lorentz force is sufficiently weak for perturbations to be damped by viscous and buoyant forces. Above it the resulting Lorentz force becomes too strong for the stabilizing forces to cancel perturbations, which then grow exponentially. This phenomenon, which results in a stack of vortices whose axis is normal to the flow of electric current is known as the TI [1] [2]. Its appearance at approximately 3 kA in an earlier version of this liquid metal experiment had previously been demonstrated with fluxgate magnetometers, which measured the vertical component of the magnetic field [3]. The experiment was since modified to carry out measurements with ultrasound Doppler velocimetry (UDV) to measure the vertical component of the liquid metal flow velocity.

2 EXPERIMENTAL SETUP

2.1 Basic setup

The core of the experiment consists of a liquid GaInSn column that is 75 cm long and 10 cm wide contained within a hollow polyoxymethylene cylinder. The top and bottom of the cylinder consist of copper electrodes connected to a water cooled switched-mode DC power supply unit (PSU) with a switching frequency of 10 kHz. Water cooling is also applied to the 3 cm wide copper conductors connecting the PSU to the electrodes, as well as the bottom electrode. Two boreholes in the top electrode each accommodate an ultrasound transducer (UST), which is in direct contact with the GaInSn [Fig 1.]. They are designed to operate at a frequency of 6 MHz and have a diameter of 12 mm.

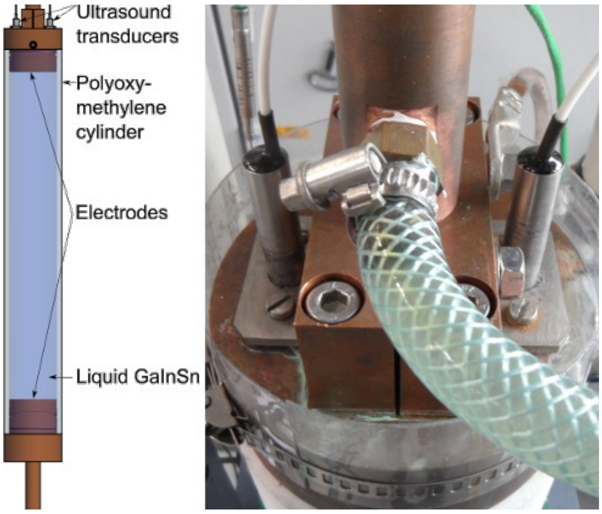

Figure 1: Left: Schematic of the GaInSn cylinder. Right: Closeup on top electrode with inserted USTs.

Although ultrasound frequencies as low as 2 MHz would have been sufficient to achieve the spatial resolution required for this experiment, the electromagnetic noise from the PSU was found to be less intense at higher frequencies. This can be reasonably attributed to the fact that the rectangular waveform of the PSU's switching can be approximated with a superposition of harmonic waves whose frequencies are odd integer multiples of the switching frequency and whose amplitudes decrease exponentially with increasing frequency. The USTs are triggered by and feed the measured signal to the Doppler velocimeter, which in turn is controlled by a data acquisition computer.

Initial attempted UDV measurements at currents of the order of 2 kA revealed that the noise was too high for velocities to be retrieved. A noise suppression system therefore had to be devised.

2.2 Noise reduction system

An assembly of six low self-inductance (15 nH) film capacitors manufactured by Electronicon was connected to the PSU's mains in parallel with the load consisting of the TI experiment to act as a shunt reducing ripples in the DC current [Tab. 1].

Hydrogen-reduced iron powder and carbonyl iron ring cores were placed around the copper conductors delivering electric current to the experiment to act as noise reduction inductors, impeding passage of time-varying current by inducing an opposing voltage. The cores were selected for having a high inductive reactance in the frequency range used for UDV in order to suppress AC ripples, as well as a high A_L value, which is defined in relation to the inductance L and number of turns of a coil, N as follows:

$$A_L := \frac{10^4 L}{(N)^2}. \tag{1}$$

A high A_L is desirable because the inductance is proportional to the energy that can be stored in the inductor's magnetic field. Here $N = 1$, as a ring core around a straight conductor is equivalent to a coil with a single turn around a core.

The inductance is constant in the regime in which the magnetic flux density within a core increases linearly with the magnetic field strength, before the saturation flux density is reached, which is above 1 T for iron powder materials. Ampère's circuital law can be used to calculate the DC magnetic flux density around the conductors feeding the experiment:

$$\oint_{2\pi r} \vec{B}\cdot d\vec{l} = \mu \int_{\pi r^2}\int \vec{J}\cdot d\vec{S}. \tag{2}$$

At the maximal possible current of 8 kA and the 1.5 cm radius of the conductor, the maximum flux density in air is about 0.1067 T.

Ring cores made by the manufacturer Amidon were employed [Tab. 2]. The maximum magnetic flux density within them can can be estimated by inserting their outer radii and permeability μ into Eq. (2). The resulting estimated flux densities are 0.5594 T, 0.1938 T, 1.4537 T for the core types T225-2, T650-2 and T650-36 respectively.

Two T650-2 cores and the T650-36 core are employed as a common-mode choke (CMC), through which current flows both to and from the experiment. The DC magnetic fields within the CMC cores therefore cancel each other out to some extent. Consequently, the resulting field within the T650-36 core is well below its saturation flux density [Fig. 2].

On the other hand, common-mode noise currents, i.e. those which travel through the choke in the same direction, do induce a magnetic field in the cores, which causes the inductor to reduce these currents.

The complex impedance of the circuit can be calculated from the data given in Tab. 1 and Tab. 2 under the assumption that the GaInSn alloy has a conductivity of 3.1×10^6 $\Omega^{-1}m^{-1}$ under experimental conditions [4]. It is further assumed that the inductors formed by the ring cores and the copper conductor have negligible parasitic capacitances and resistances. The real part of the circuit's impedance peaks near the 2 MHz region (at 1.74 MHz) [Fig. 3]. 2 MHz USTs were in fact used for the first UDV measurement attempts in this experiment, but the signal proved to be less noisy with higher frequency USTs, even though the primary circuit resonates closer to 2 MHz.

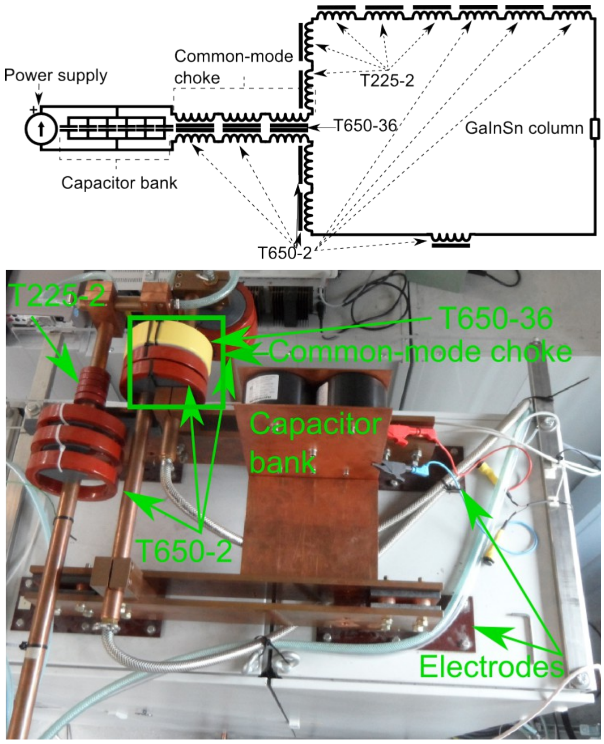

Figure 2: Top: Circuit diagram of the experiment. Bottom: Noise suppression assembly on top of the power supply unit.

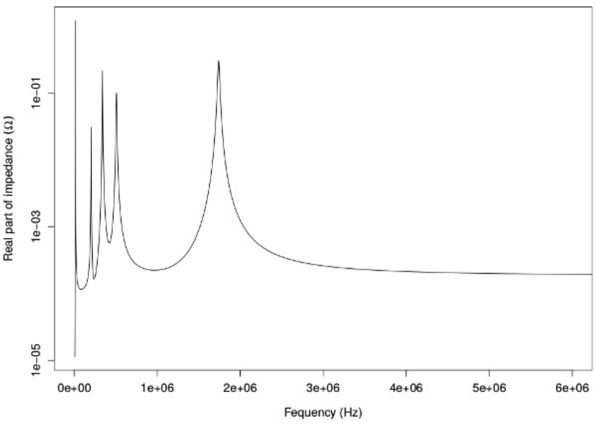

Figure 3: Real part of the circuit's complex impedance as a function of AC ripple frequency.

Additional noise suppression was attempted by winding the coaxial cables connecting the USTs to the velocimeter around toroidial ferrite cores manufactured by Amidon designated “FT140-75” and “FT140-77” as well as split cores manufactured by Würth Elektronik designated “STAR FIX LFS with Safety Lock 74272722”. According to the manufacturer of the latter, the impedance at one turn is 30 Ω for 1 MHz and 45 Ω for 10 MHz. The former two have A_L values of 6700 and 2545 respectively. Each cable was wound around the toroidal cores nine times and four times around the split core. This resulted in the real part of the total impedance being 120 at 1 MHz and 180 Ω at 10 MHz. The effect of the ferrite cores on the noise affecting UDV measurements was however less significant than that of the filtering assembly attached to the primary circuit driving the experiment.

In order to prevent ground loops caused by nearby electronic equipment from affecting measurements, the Doppler velocimeter was decoupled from the electric grid by means of an isolation transformer. Its primary and secondary coil are shielded by a magnetic core, permitting passage to AC signals whilst dampening common-mode noise.

2 MEASUREMENTS AND DATA ANALYSIS

The principal information gathered from UDV measurements are the relative intensities of echoes produced by metal oxide scatterers in the liquid alloy, as well as their wavelength shifts, from which the velocimeter computes a velocity in real time. The critical current at which the TI begins to set in is approximately 2.6 A and has wavelength of approximately 12.5 cm [2][3]. However, other effects, such as thermal convection and electrovortex flow driven by the electrodes begin to set in at much lower currents.

Velocity fields of spatially alternating upward and downward motion are measured by the two USTs [Fig. 4, 5]. The spatial and velocity resolutions are 0.91 mm and 0.36 mm/s respectively and the pulse repetition period is 2.5 ms, with 150 pulses per profile. At depths in which an upward motion is measured by one sensor, the other measures a downward velocity and vice versa. The dominant vertical period of the velocity fields is approximately twice as large as that of the TI, suggesting that it is being dwarfed by the other aforementioned phenomena.

Recent simulations of the non-TI-related flow in the column have provided preliminary results that hint at a stable helical motion, which is not inconsistent with measurements [5].

Because of those varied processes, it is necessary to spectrally analyse the velocity field, if modes consistent with the TI are to be isolated. To accomplish this, a least squares spectral density estimate using the Lomb-Scargle method of the velocity data can be performed [Fig. 5]. The periodicity (expressed as wave numbers) of the flow patterns visible in fig. 4 is evident. A mode with a wave number of approximately 8 m^{-1} (i.e. the characteristic 12.5 cm wavelength of the TI) is present as well, albeit much less pronounced. A more in-depth analysis will be necessary, such as the isolation of individual wave number bands and comparing them to each other's growth rates as well as the growth rate of the TI.

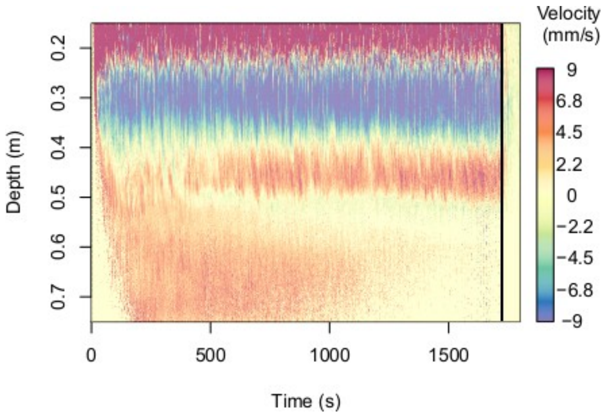

Figure 4: Vertical velocity distribution in the GaInSn column with a current of 3.75 kA. As indicated by the vertical black line, the current is switched off after 28.5 minutes due to overheating of the upper electrode. As a result the flow pattern is immediately disrupted, indicating that it is driven by the current.

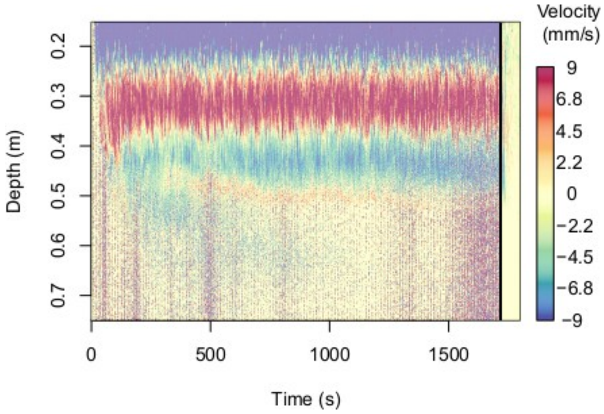

Figure 5: The vertical velocity distribution as measured by the other UST during the same iteration of the experiment.

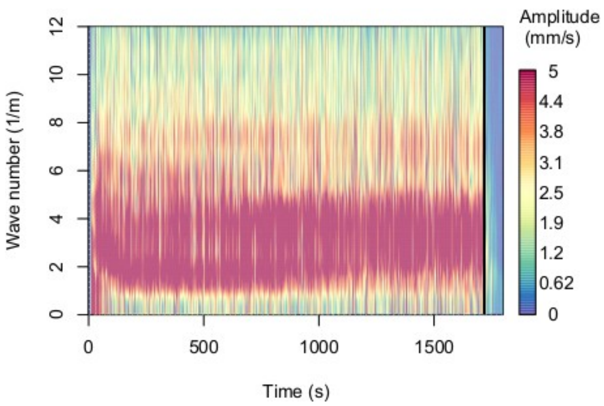

Figure 6: Lomb-Scargle periodogram of the velocity time series in fig. 4.

TABLES

Table 1: Capacitance and equivalent series resistance of the capacitors used as a shunt in the primary circuit.

Type	C (µF)	R_S (mΩ)	Quantity
E53.H59-471T10	0.47	2.9	1
E53.H59-472T10	4.7	1.3	2
E53.M59-103T20	10	0.6	1
E53.R60-333T20	33	0.2	1
E53.R60-530T20	50	0.3	1

Table 2: Properties of the cores used to reduce noise in the primary circuit. The number preceding the dash in the type name equals the outer diameter in hundredths of inches and the number following it indicates the material type as designated by Amidon.

Type	T225-2	T650-2	T650-36
Initial $\mu_r = \mu/\mu_0$	10	10	75
A_L value (µH/N^2)	120	580	4340
Frequency range (MHz)	2 – 30	1 – 30	0.01 – 1
Outer radius (mm)	28,6	82,55	82,55
Quantity	5	8	1

3 SUMMARY AND OUTLOOK

The basic feasibility of UDV within a high-current electrode has been shown and preliminary results are in general agreement with previous B_z-measurements [3]. However, it has not yet been determined whether the growth rate of the detected modes is consistent with the TI. The next steps involve the addition of two more USTs to measure the vertical flow 90° off the position of the current sensors, as well as further analysis of the collected data, including the development of algorithms.

REFERENCES

[1] Spruit H. C.: Dynamo action by differential rotation in a stably stratified stellar interior, Astronomy & Astrophysics 381 (2002), 923–932.
[2] Weber N. et al.: Numerical simulation of the Tayler instability in liquid metals, New Journal of Physics 15.4 (2013), 043034
[3] Seilmayer et al.: Experimental evidence for a transient Tayler instability in a cylindrical liquid-metal column, Physical Review Letters, *108*(24), (2012). 244501-1–244501-4 .
[4] Morley N.B. et al.: GaInSn usage in the research laboratory, Review of Scientific Instruments 79.5 (2008), 056107
[5] Weber N.: unpublished, personal communication